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Fuel cells: The expectations for an environmental-friendly and sustainable source of energy

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A B S T R A C T

It is a well known fact that eight countries have 81% of all world crude oil reserves, six countries have 70% of all natural gas reserves and eight countries have 89% of all coal reserves. Energy is central to achieving the interrelated economic, social, and environmental aims of sustainable human development. But if we are to realise this important goal, the kinds of energy we produce and the ways we use them will have to change. Otherwise, environmental damage will accelerate, inequity will increase, and global economic growth will be jeopardised. Energy produced and used in ways that support human development in all its social, economic and environmental dimensions is what is meant by sustainable energy. The generation of energy by clean, efficient and environmental-friendly means is now one of the major challenges for engineers and scientists. This paper reviews a proposed energy-related solution to global warming, air pollution mortality, and energy security. It discusses recent topics related directly to energy production such as fuel cells (FCs) which represent a promising clean and efficient energy conversion technology. The paper also focuses on those technologies which, in terms of cost, cleanliness, reliability and availability, have the potential to compete with conventional energy conversion systems and to reach commercialisation phase before 2015.

Contents

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1. Introduction

Energy is the most important resource for the development of a country and the utilisation of energy per capita is increasing tremendously. In fact Energy security, Economic growth and Environmental protection (the three E's) are the national energy policy drivers of any country of the world [1]. In addition, it is not secret that fossil fuel supplies are dwindling and will eventually be depleted within a few decades. At the same time, fossil fuel consumption continues to increase leaving in its wake destructive cumulative effects, which began during the industrial revolution. Such ever-increasing demand could place significant strain on the current energy infrastructure and potentially damage the world environment and people's health. Scientists, governments, and industries are witnessing the long-term consequences of energy consumption and foresee catastrophic outcomes if alternative methods of energy production are not developed and utilized to meet the needs of our global economy. Because FCs, as electrochemical devices, convert fuels such as hydrogen into electricity without combustion, they create virtually no pollution and hold the key to future prosperity and a healthy global environment. In recent years, the development and commercialisation of FC systems for different applications is increasing tremendously and is proposed as a competitive energy policy and a step forward to the target of sustainable development and environmental friendly energy source. FCs are also considered a promising energy conversion technology of the future owing to inherent advantages of electrochemical conversion over thermal combustion processes. They are static energy conversion devices that convert the chemical reaction of fuels directly into electrical energy cleanly and efficiently using hydrogen or hydrocarbons as the fuel and produces water as its by-product. They are more efficient in converting energy to electricity (work) than internal combustion engines and most combustion systems. Because of the more favourable environmental impact and more efficient energy conversion, FCs are viewed by many as the energy source of the 21st century. The 19th century was known as the Age of the Steam Engine and the 20th century was seen as the age of the Internal Combustion Engine. Similarly, some believe the 21st century will be the age of the FCs because they are much in the news since they appear to be one of the most efficient and effective solutions to environmental problems that we face today (global warming, air pollution, acid precipitation, ozone depletion, forest destruction, and emission of radioactive substances). World oil production will decline in the next 20–40 years and dependence on energy from fossil fuels is also reaching its limits (Figs. 1 and 2) [2], the development of new power generation technologies will become increasingly important. Simultaneously, interest will likely increase regarding energy-related environmental concerns to take precautions today for a viable world for coming generations. Indeed, energy is one of the main factors that must be considered in discussions of sustainable development.

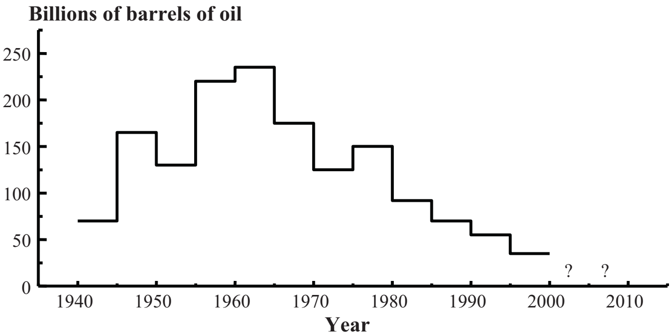

Fig. 2. Volume of oil discovered world wide every 5 years.

Everyday some 250,000 global citizens are born; each is requiring clean and affordable energy to provide the basics of life. As world populations grow, many faster than the average 2%, so that it is expected to reach 9 billions in 2050 as seen in Fig. 3 and Table 1 [3,4], the need for more and more energy is exacerbated, as illustrated in Tables 1 and 2 [5].

Enhanced lifestyle and energy demand rise together and the wealthy industrialized economies which contain 25% of the world's population consume 75% of the world's energy supply [6]. Global demand for energy services is expected to increase by as much as an order of magnitude by 2050, while primary-energy demands are expected to increase by 1.5 to 3 times [7]. Worldwide electricity demand is generally projected to grow at 2.3% to 3.4% annually in the coming decade. If every person on earth could access 2 kW

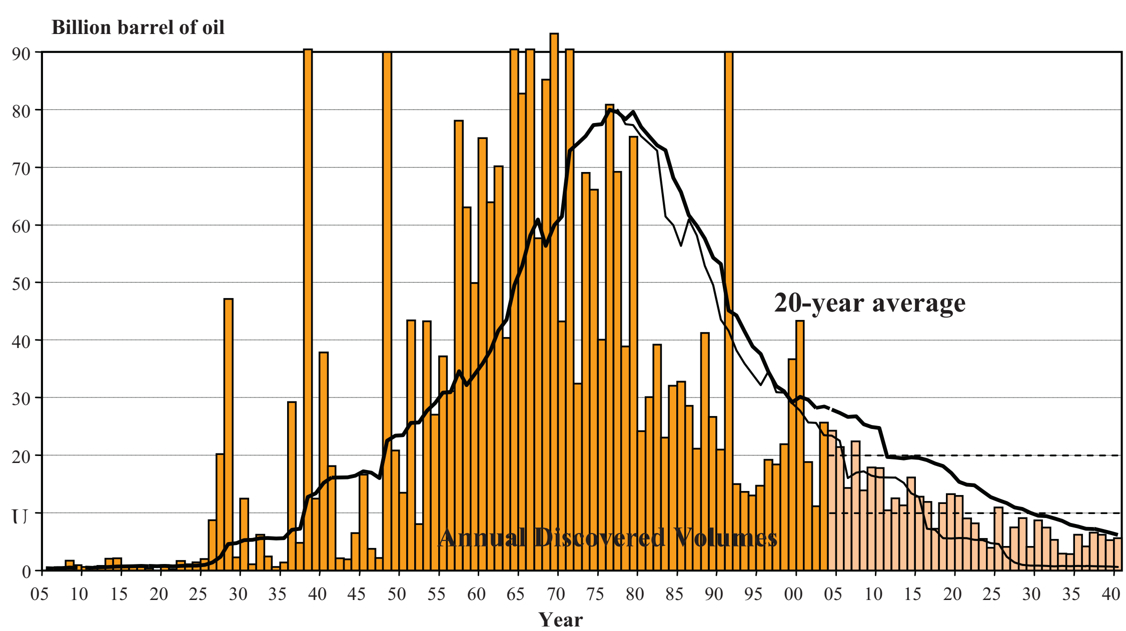

Fig. 1. Confronting the supply challenges, annual discovered volume of oil (1905–2040).

Table 1
Population, energy and electricity demands.

Year	Population (billions)	Energy demand (MMBDOE)*	Electricity demand % of energy demand
1985	High: 4.8, median: 4.8, low: 4.8	200	9
1995	High: 5.3, median: 5.3, low: 5.3	300	15
2000	High: 6.1, median: 6.1, low: 6.1	350	30
2020	High: 8.5, median: 8.1, low: 7.8	510	45
2050	High: 12.5, median: 9.1, low: 9	700	62
2100	High: 20, median: 14, low: 10.5	1200	80

* Millions of barrels per day of oil equivalent.

Table 2
World marketed energy consumption by country grouping, 2006–2030 (Quadrillion Btu = 1.055 Exajoule).

Region	2006	2010	2015	2020	2025	2030	Average annual change (%)
OECD	241.7	242.8	252.4	261.3	269.5	278.2	0.6
North America	121.3	121.1	125.9	130.3	135.6	141.7	0.6
Europe	81.6	82.2	84.8	87.9	90.0	91.8	0.5
Non-OCED	230.8	265.4	299.1	334.4	367.8	400.1	2.3
Europe and Eurasia	50.7	54.0	57.6	60.3	62.0	63.3	0.9
Asia	117.6	139.2	163.2	190.3	215.4	239.6	3.0
Middle East	23.8	27.7	30.3	32.2	34.6	37.7	1.9
Africa	14.5	16.2	17.7	19.1	20.6	21.8	1.7
Central and South America	24.2	28.3	30.3	32.5	35.2	37.7	1.9
Total World	472.4	508.3	551.5	595.7	637.3	678.3	1.5

Fig. 3. World population, the growth.

of electricity, the peak demand for electric power could increase from its current level of 20.4 TW to 90 TW [8]. Hydrocarbons energy sources cannot be expected to fill that increased demand and should not be, for both environmental and practical economic reasons (Fig. 4) [9]. Energy consumption in developed countries grows at a rate of approximately 1% per year, and that of developing countries, 5% per year [10].

In response to the critical need for a cleaner energy technology, some potential solutions have evolved including energy conservation through improved energy efficiency, reduction in the consume of fossil fuels and an increase in the supply of environmental-friendly energy such as renewable sources and FCs. Electricity from fuel cells can be used in the same way as grid power. Large-scale, utility-based FC power generation systems have reached pilot-scale demonstration stages in the U.S.A., Europe, and in Japan. Small-scale FC systems are being developed for military, residential, industrial, and transportation applications.

FCs are electrochemical electricity generators of high efficiency which concomitantly can produce heat at temperatures which range from 50 to 1000 °C. With fuels such as oil, coal or natural gas the pollutant emission levels are 10–1000 times lower than in conventional energy conversion systems depending on the type of application. When a carbon-containing fuel is used, the CO_2 emissions are significantly lower than in conventional systems, due to the higher efficiency. With hydrogen as a fuel the pollutant emission is zero at the point of use (the production of hydrogen may generate polluting emissions). FCs can be used in a wide range of applications meeting energy demand: electricity production, cogeneration, road transport, ships, trains, portable and current

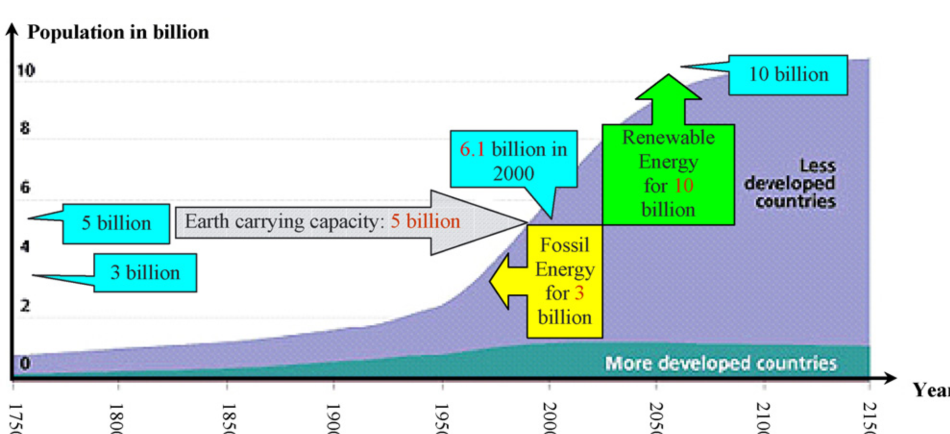

Fig. 4. World population growth and carrying capacity of Earth.

critical devices, etc. FC systems have a good part load behaviour, are easy to operate, require short construction times due to a high level of modularity, and should need low maintenance since no rotating parts are needed (except for some auxiliaries). They are a promising alternative for small/medium scale decentralised electricity generation and in particular for combined heat and power (CHP) production. The interest of FCs is based on their potential for energy savings and cleaner energy conversion, the impact on employment in the long term and industrial competition on a worldwide scale. Fuel cells are static energy conversion devices that convert the chemical reaction of fuels directly into electrical energy and produces water as its by-product.

2. Environmental problems

Environmental problems span a continuously growing range of pollutants, hazards and ecosystem degradation over wider areas. Technological progress has dramatically changed the world in a variety of ways. It has, however, also led to developments of environmental problems which threaten man and nature. During the past two decades the risk and reality of environmental degradation have become more apparent. Growing evidence of environmental problems is due to a combination of several factors since the environmental impact of human activities has grown dramatically because of the sheer increase of world population, consumption, industrial activity, etc. Recently environmental concern has extended, in addition to the conventional effluent gas pollutants such as SO_2, NO_x, particulates, and CO, to the control of micro or hazardous air pollutants, which are usually toxic chemical substances and harmful in small doses, as well as to that of globally significant pollutants such as CO_2, the main greenhouse gas responsible for global warming. Aside from advances in environmental science, developments in industrial processes and structures have led to new environmental problems such as, in the energy sector, major shifts to the road transport of industrial goods and to individual travel by cars has led to an increase in road traffic and hence a shift in attention paid to the effects and sources of NO_x and volatile organic compound emissions. The main areas of environmental problems are:

- Major environmental accidents
- Air pollution
- Water pollution
- Maritime pollution
- Land use and siting impact
- Radiation and radioactivity
- Solid waste disposal
- Hazardous air pollutants
- Ambient air quality

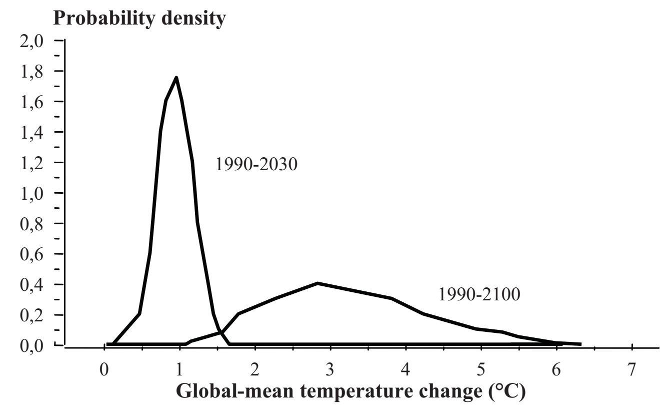

Fig. 5. Global-mean temperature change over the period of 1990–2100 and 1990–2030.

- Acid precipitation
- Forest destruction
- Ozone depletion, and
- Global warming (greenhouse effect).

Build-up of carbon dioxide and other greenhouse gases is leading to global warming with unpredictable but potentially catastrophic consequences. According to the U.S. Department of Energy, world emissions of carbon are expected to increase by 54% above 1990 levels by 2015 making the earth likely to warm 1.7–4.9 °C over the period 1990–2100, as shown in Fig. 5 [11].

Global temperatures in 2001, for example, were 0.52 °C above the long-term 1880–2000 average (the 1880–2000 annually averaged combined land and ocean temperature is 13.9 °C). In June 2003, temperature anomalies were 2.3 °C higher with respect to 1961–1990 based periods.

During the past century, global surface temperatures have increased at an average rate of 0.6 °C/century. Temperature rise during the last 70 years is 2.3, 1.3 and 1.7 °C according to the three centres assessing this phenomenon, i.e., Princeton in the U.S.A., Hamburg in Germany, and IPCC of London in U.K. Average temperature of the Atlantic, Pacific and Indian Oceans (covering 72% of the earth surface) has risen by 0.06 °C since 1995 [12]. Table 3 estimates the global climate change around 2050 [13].

Fossil fuel is rising temperatures, rising oceans, Fig. 6 shows the historic relationship temperature – sea level [14,15].

When fossil fuels burn, they emit toxic pollutants that damage the environment and people's health. The emission of fine particulate matter, from the burning of coil, oil, diesel fuel, gasoline and wood can potentially lead to respiratory problems and cancer. World wide, over two billion people living in urban areas suffer from severe air pollution with over 1,700,000 deaths resulting

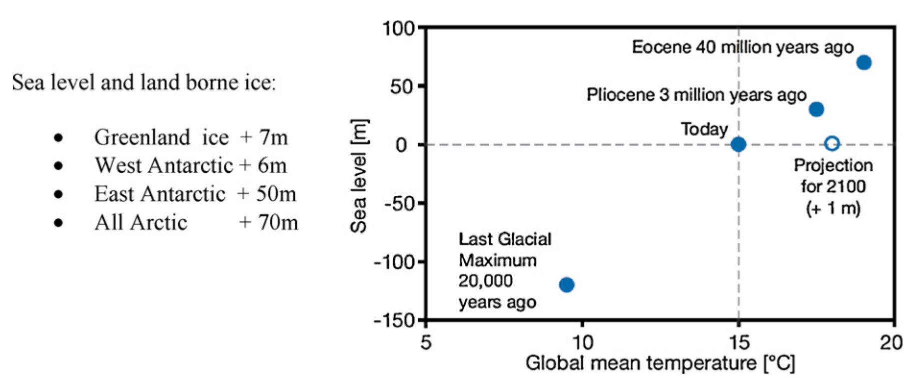

Fig. 6. Historic relation temperature – sea level.

Table 3
Global climate change estimate around 2050.

Scenario	T increase (°C)	Seas level rise (cm)	CO_2 concentration (ppmv)*
Low	0.9	12	467
Medium low	1.5	18	443
Medium high	2.1	25	554
High	2.4	67	528

* Part per million by volume.

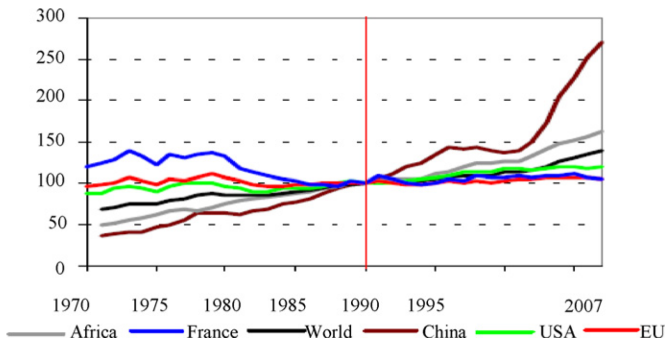

Fig. 7. Global CO_2 emissions in million of tonnes.

each year, according to the World Bank [16]. Moreover, each gallon of gasoline produced and used in an internal combustion engine releases roughly 12 kg of CO_2 that contributes to global warming. The world's energy consumption today is estimated to 536 exajoules with 80–90% derived from the combustion of fossil fuels. About 8.6 billion metric tonnes carbon equivalent of greenhouse gas emission are released in the atmosphere to meet this energy demand [17]. Approximately 80% is due to carbon emissions from the combustion of energy fuels [17]. Estimates of future data suggest that developing countries are the fastest growing source of CO_2 emissions in that 17 major developing countries will reach the emission level of 3.6 billion tonnes in 2025 compared to 0.9 billion tonnes in 1985 [18]. This can be reduced through efficiency improvements and fuel-switching measures. Table 4 is an example of CO_2 emissions (in tonnes) per head of population in ten regions of the world. It is worth noticing that the U.S.A. produces five times the world average emission and according to the US Environmental Protection Agency, energy generation and motors vehicles in the US account for 88% of all CO_2 emissions. Fig. 7 also shows the global CO_2 emissions in six different regions [19].

According to the special report on emission scenarios issued by the IPCC under the auspices of the United Nations (UN), by the end of the 21st century, nations could expect to see CO_2 concentrations of anywhere from 490 to 1260 ppmv (75–350% above the pre-industrial concentration). IPCC states that average global temperatures are projected to increase by 1.4–5.8 °C over the next 100 years because of the enhanced greenhouse effect. Precipitation is also expected to increase over the 21st century, particularly at northern mid-high latitudes, though the trends may be more variable in the tropics. Snow extent and sea-ice are also projected to decrease further in the northern hemisphere. Glaciers and ice-caps are expected to continue to retreat. Glaciers and the polar ice caps are expected to melt, causing sea levels to rise by between 9 and 88 cm in the coming century (see Fig. 6). Significant changes to patterns of rainfall including monsoons and more extreme weather events are expected.

The global energy economy will need to decarbonise power generation substantially in order to achieve a sustainable energy future. This will require large-scale shifts to renewable energy for power generation. The International Energy Agency has identified Hydrogen FCs as one of the key technologies that are at the heart of the energy technology revolution because they can make the largest contributions to reducing greenhouse gas emissions. Recently environmental concern has extended to the control of micro or hazardous air pollutants, which are usually toxic chemical substances and harmful in small doses.

3. Fuel cells

FCs can be thought of as solid state generators that generate electricity and heat by electrochemically combining a gaseous fuel (hydrogen) and an oxidant gas (oxygen from the air) through electrodes and across an ion conducting electrolyte. During this process, water is formed at the exhaust. The FC does not run down or require any recharging; unlike a battery it will produce energy as long as it is continuously replenished of reactants (fuel and oxidizer) while reaction products are discharged to the external. The principal characteristic of a FC is its ability to convert chemical energy directly into electrical energy giving much higher conversion efficiencies than any conventional thermo-mechanical system (two or three times the efficiency of all present electricity generators) thus extracting more electricity from the same amount of fuel, operation without combustion so they are virtually pollution free and quieter operation since there are no moving parts needing maintenance. This shows how important fuel cells will be to the human race.

3.1. Historical notes

Despite their modern high-technology aura, FCs actually have been known to science for more than 160 years and have become the subject of intense research and development, especially since World War II. Alessandro Volta (1745–1827) was the first scientist to place the observations of the electrical phenomena on a scientific footing. J. W. Ritter (1776–1810), also known as the founder of the electrochemistry, has continued to develop the understanding of electricity. Decades before the invention of the internal combustion engine, Sir Humphrey Davy created, in 1802, a simple FC based upon a compound (C/H_2O, $NH_3/O_2/C$) delivering a feeble electric shock. The discovery of the principle of the FC is due to Christan Friedrich Schönbein from 1829 to 1868. He described his finding in a letter sent to Michael Faraday in summer 1838. Sir William Grove (1811–1896), an English lawyer turned scientist, won renown for his development of an improved wet-cell battery in 1838, the

Table 4
Global CO_2 emissions in tonnes/capita (2008).

U.S.A.	Australia	Russia	Japan	E.U.	M. East	China	E. East	L. America	Africa	World average
19	19	11.1	9.5	8.1	6.8	4.3	2.8	2.1	0.9	4.3

"Grove cell", as it came to be called. This cell type is based on reversing the electrolysis of water [20]. His FC used dilute sulphuric acid as the electrolyte and operated at room temperature. FC, named also as a gas battery, has been the main interest of Grove from 1842 till 1844. Ceramic FCs came much later and began with Nernst's discovery of solid oxide electrolytes in 1899 [21]. Ludwig Mond (1839–1909) spent most of his career developing industrial chemical technology. Mond and assistant Carl Langer (1935) described their experiments with a hydrogen–oxygen fuel cell that attained 6 amps per square foot (measuring the surface area of the electrode) at 0.73 volts. Friedrich Wilhelm Ostwald (1853–1932), a founder of the field of physical chemistry, provided much of the theoretical understanding of how FCs operate. Emil Baur (1873–1944) of Switzerland conducted wide-ranging research into different types of fuel cells during the first half of the 20th century. Baur's work included high temperature devices (using molten silver as an electrolyte) and a unit that used a solid electrolyte of clay and metal oxides. The operation of the first ceramic fuel cell at 1000 °C, by Baur and Preis, was revealed in 1937 [22]. The first working FCs were not developed until 1932 by Francis Bacon. Francis Thomas Bacon (1904–1992) began researching alkali electrolyte fuel cells in the late 1930s. In 1939, his first cell was built. Since 1945, three research groups (US, Germany and former USSR) took over the studies on some principal types of generators by improving their technologies for industrial development purpose, but development was slow until 1959 when Francis Bacon + Co. built a five-kilowatt system and Harry Karl Ihrig built a twenty-horsepower FC propelled tractor. These works yielded the actual concepts, namely at Siemens and Pratt & Wittney [23]. In connection with the space program Apollo in 1960, NASA decided that fuel cells were the best way of generating power (and water) in space spent tens of millions of dollars in a successful program that used hydrogen-based fuel cells to power the on-board electrical systems on the Apollo journey to the moon. Beginning in the mid-80s, government agencies in the U.S.A., Canada and Japan significantly increased their funding for FC R&D with several hundred units of the first type commercialised, at a very modest level for stationary power use, being installed around the world generating 200–250 kW by mainly using natural gas. Starting in the 1990 Ballard, a leader in FCs making, put its fuel cells into a series of increasingly impressive prototype buses that run on compressed hydrogen. The first small bus rolled out for the media in 1993. In the late 90s, six Ballard-built fuel cell transit buses were put onto the street of Chicago and Vancouver.

Today, FCs are common in space flight, transportation, portable power, home power generation and large power generation (11 MW unit is operating and hundreds of smaller units are operational powering buses and as stationary power generators).

3.2. FC benefits

FC technology is the most demanding from a materials standpoint and is developed for its potential market competitiveness arising from:

- Energy security
  - reduce oil consumption;
  - cut oil imports;
  - increase the amount of the country's available electricity supply
- Reliability
  - achieves operating times in excess of 90%;
  - power available 99.99% of the time;
  - minimal degradation (<0.1%/1000 h)
- Low operating cost
  - the efficiency of the fuel cell system will reduce drastically the energy bill (mass production of fuel cells);
  - minimal installation;
  - minimum degradation;
  - low maintenance;
  - ease of licensing
- Constant power production
  - Generates power continuously unlike backup generators, diesel engines or uninterrupted power supply;
  - high availability/reliability;
  - high quality power;
  - optional steam/hot water cogeneration;
  - operating temperature ranging from 50 to 1000 °C;
  - excellent shelf life
- Choice of fuel
  - fuel selection and flexibility;
  - natural gas, propane, butane, biogas, propane, methanol and diesel fuel
- Clean emissions
  - environmentally friendly;
  - 100–1000 times cleaner than the 1998 American clean bus standards;
  - compared with traditional combustion power plants:
    - avoids the production of 180 tonnes/year of CO_2;
    - avoids the environmental pollution of 1035 kg/year of NO_x;
    - keeps NO and SO_2 from being released into environment therefore eliminates 20,000 kg/year of acid rain and smog-causing pollutants from the environment;
    - reduce carbon dioxide emissions by more than 2 million kg/year;
    - avoids the import of 77 tonnes/year of oil equivalent
- Quit operations
  - unattended operation;
  - low noise, quit enough to be installed indoors;
  - normal conversation possible near to fuel cell;
  - sound proofing or hearing protection is not required as for the combustion engines
- High efficiency
  - potential in the stationary and portable power;
  - converts up to 50–70% of available fuel to electricity (90% with heat recovery);
  - reduces fuel costs and conserves natural resources

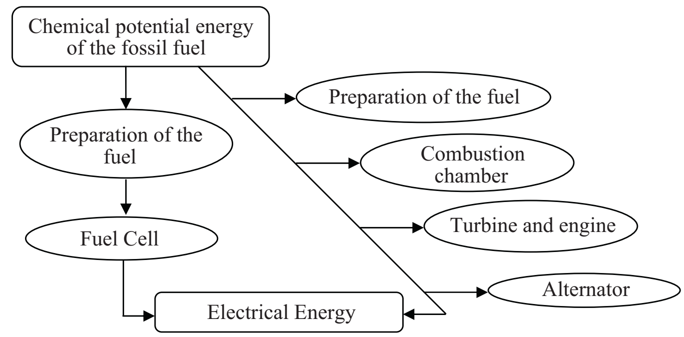

Fig. 8. Comparison of the conversion of energy between a fuel cell and a thermal power plant.

A comparison of the conversion of energy between a fuel cell and a thermal power plant is depicted in Fig. 8. Three examples are given in Table 5 illustrating the last three criteria of FC benefits [24]. Table 6 shows a comparison of different generation systems [25]. It is observed that the efficiency of fuel cells is always higher as compared with conventional system and other distributed generation systems. While comparing the fuel cell with other distributed generation technologies, it offer more advantages like high energy conversion efficiency, zero emission, modularity, scalability, quick

Table 5
Typical FC characteristics.

Air emissions*	SO_x	NO_x	CO	Particles	Organic compounds	CO_2
Effluent gas emissions						
Fossil fuelled plant	28,000	41,427	28,125	500	468	4,044,000
FC	0	0	72	0	0	1,860,000

Means	Gas-electric	Micro turbine	Diesel-electric	FC	Social conversation
Sound effects					
Sound level	High	Moderate	High	Low	Low**
Sound proofing required	Yes	Yes	Yes	No	No

Means	Gas-electric	Micro turbine	Diesel-electric	FC
Efficiency	20%	24%	32%	90% with 30–40% heat recovery

* Pounds of emissions per 1650 MWh from one year full operation.
** Similar to fuel cell sound level.

installation and gives good opportunities for cogeneration operations [26,27].

Today FC technology already achieves highest electrical efficiencies in the mid to lower power rating range and has the potential to be advantageous versus central power generation in the future.

3.3. Operating concept of FCs

FCs consist of two catalytic and relatively stable electrodes sandwiched around an electrolyte. The fuel is also important as the principal parameter but independent of the other as it is most of the time converted into hydrogen. Many combinations of fuel and oxidant are possible namely: hydrogen as a fuel and oxygen as oxidant, carbon oxide, hydrocarbons and alcohols as fuel and air, chlorine and chlorine dioxide as oxidant.

FCs produce power without any moving parts to wear out by combining hydrogen atoms with oxygen atoms. As long as they are supplied with a hydrogen containing fuel and an oxygen atoms (possibly air) they will produce power.

3.3.1. Parameters of FCs

An elementary FC essentially needs only five fundamental components that are:

(1) An anode, porous to allow fuel to enter in contact with the electrolyte without itself being consumed or corroded. It disperses the hydrogen gas equally over its whole surface and conducts the electrons that are freed from hydrogen molecule, to be used as a useful power in the external circuit.
(2) A cathode to allow oxidizer to enter in contact with the electrolyte without itself being consumed or corroded. It distributes the oxygen fed to it onto its surface and conducts the electrons back from the external circuit where they can recombine with oxygen ions, passed across the electrolyte, and hydrogen to form water.
(3) An electrolyte that works as a conductor of negative or positive ions. The electrolyte (such as phosphoric acid, solid oxide or an appropriate polymer) determines the operating temperature of the FC and is used to prevent the two electrodes to come into electronic contact by blocking the electrons. It also allows the flow of charged ions from one electrode to the other to maintain the overall electrical charge balance. It can either be an oxygen ion conductor or a hydrogen ion (proton) conductor, the major difference between the two types is the side in the FC in which the water is produced: the oxidant side in proton-conductor fuel cells and the fuel side in oxygen-ion-conductor ones, as shown in Figs. 9 and 10.
(4) O_2 interconnect wire

The catalyst is used in order to facilitate the reaction of oxygen and hydrogen. This can be a platinum coating or nickel. The catalyst on the anode, for example, promotes the oxidation of hydrogen molecules into hydrogen ions (H^+) and electrons: the hydrogen ions migrate through the membrane to the cathode, where the cathode catalyst causes the combination of the hydrogen ions, electrons and oxygen to produce water.

3.3.2. Principle of fuel cell technology

The chemical energy present in hydrogen and the oxidant (oxygen) is cleanly, quietly and efficiently converted electrochemically into electrical energy. The hydrogen, under the action of the catalyst, splits into protons (hydrogen ions) and electrons, which take different paths towards the cathode. The proton passes through the electrolyte (such as phosphoric acid, solid oxide or an appropriate polymer) and the electron create a separate current that can be used before reaching the cathode, to be reunited with the hydrogen and oxygen to form a pure water molecule and in some varieties of cells a lot of heat raising efficiency to 90% of the latent heat of the fuel and heat (the structure of a simplified FC is shown in Fig. 9). The chemical reactions involved in the anode and cathode and its over all reactions are given as:

Anode reaction:

$$H_2 \Rightarrow 2H^+ + 2e^-$$

Cathode reaction:

$$½O_2 + 2H^+ + 2e^- \Rightarrow H_2O$$

Overall reaction:

$$H_2 + ½O_2 \Rightarrow H_2O$$

Table 6
Comparison of different energy generation systems.

	Reciprocating engine: diesel	Turbine generator	Photovoltaics	Wind turbine	Fuel cells
Capacity range	500 kW to 5 MW	500 kW to 25 MW	1 kW to 1 MW	10 kW to 1 MW	200 kW to 2 MW
Efficiency	35%	29–42%	6–25%	25%	40–60%
Capital cost ($/kW)	200–350	450–870	6600	1000	1500–3000
O&M cost ($/kW)	0.005–0.015	0.005–0.0065	0.001–0.004	0.01	0.0019–0.0153

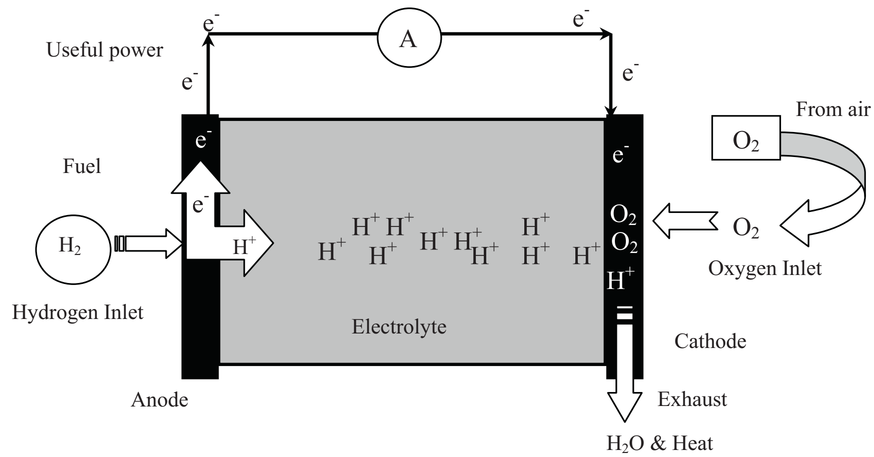

Fig. 9. Typical FC configuration based on hydrogen-proton conductor.

As already mentioned, FCs also work by producing oxygen ions at one electrode which passes through the electrolyte to the other electrode to react with its atoms of the other chemical producing power, water and heat (see Fig. 10).

The flow of electrons through the external circuit produces electric current, which can be used, for example, by a direct current (DC) electric motor. An inverter provides alternating current (AC) for modern day applications. The only by-product of this process is a pure water molecule (H_2O) and heat. Fig. 10 reactions include:

Anode side:

$$H_2 + O^{2-} \Rightarrow H_2O + 2e^-, CO + O^{2-} \Rightarrow CO_2 + 2e^-, CH_4 + 4O^{2-}$$
$$\Rightarrow 2H_2O + CO_2 + 8e^- (\text{Fuelcontaininghydrogen})$$

Cathode side:

$$O_2 + 4e^- \Rightarrow 2O^{2-}$$

Overall reaction:

$$H_2 + ½O_2 \Rightarrow H_2O$$

FCs come in many forms and most individual unit produces between 0.5 and 1.23 volts of DC electricity. To produce significant amounts of power, practical FC elements can be combined to form a series array of units or stack, analogous to a multi-layered sandwich to produce power as required. Fig. 11 shows a typical planar flat-plate stack configuration in which hydrogen and air flow down channels in the bipolar plates, where on one side each electrode face is exposed to the reactant gases. Oxygen entering the cathode compartment is adsorbed and diffuses to the electrode–electrolyte interface and is reduced (i.e., gain of electrons) by the incoming electronic charge. The planar flat-plate stack configuration is used for its relative ease of manufacture and reduced energy losses. The bipolar plates have two functions: transmission of electrons through the elementary cells and release of heat to the external environment.

The stack is the main component of the power section in a FC power plant in which cell assemblies, each including an anode, electrolyte, and cathode, are stacked with interconnecting plates between them that connect the anode of one cell to the cathode of the next cell in the stack. The plates are generally used for their high electronic conductivity, their stability in the fuel cell environment and their compatibility with other cell components.

3.4. Fuel cell types

FCs are generally classified by the chemical characteristics of the electrolyte which defines the operating temperature and at that temperature a suitable catalyst is to be selected. Presently height major different types of FCs are available as summarised in Table 7. The comparison is based on their inlet fuels, electrolyte material, operating temperature, cost, efficiency and their suitability of CHP applications. The type of electrolyte used dedicates their performance characteristics, making each type of fuel cell suitable for particular applications. The first five types are characterised by their

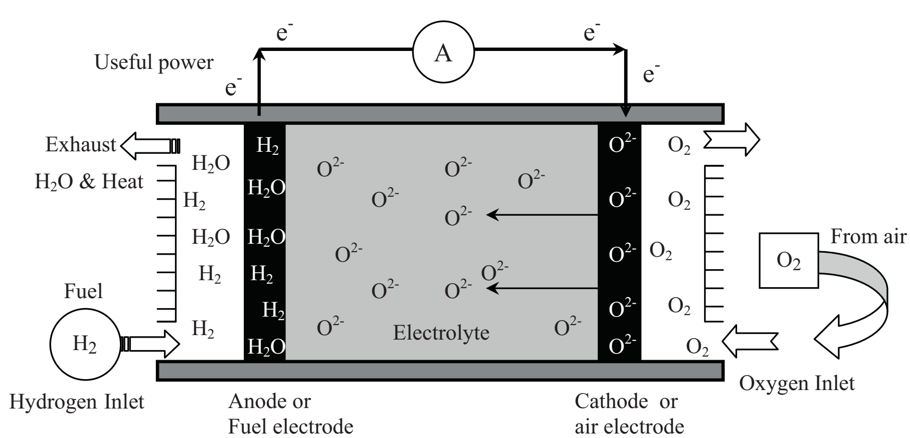

Fig. 10. Typical FC configuration based on oxygen-ion conductor.

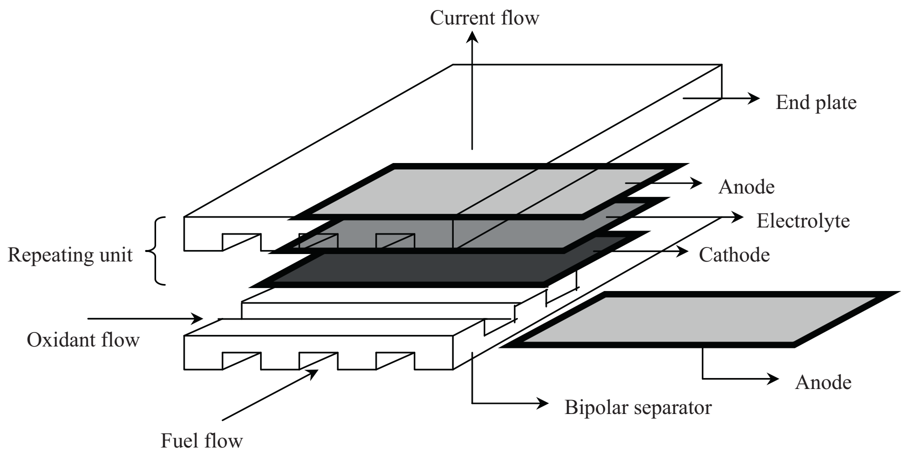

Fig. 11. Typical planar flat-plate stack configuration.

low to medium temperature of operation (50–210 °C), their relatively low electrical generation efficiencies (40–50% when operated on readily available fuels such as methanol and hydrocarbons, 50% when using pure hydrogen fuel). The latter three types are characterised by their high temperature of operation (600–1000 °C), their ability to utilise methane directly in the fuel cell and thus their high inherent generation efficiency (50–60% for common fuels such as natural gas, 90% with heat recovery) [28].

There are also other types of fuel cells which are less employed but may later find a specific application. Examples are the air-depolarised cells, sodium amalgam cells, biochemical fuel cells, inorganic redox cells, regenerative cells, alkali metal-halogen cells, etc. [7]. Present materials science has made the fuel cells a reality in some specialised applications.

The AFC is one of the earlier fuel cell system employed for NASA's space missions. It uses an aqueous solution of the potassium hydroxide as an electrolyte. It transports negative charged ions from anode to cathode and releases water as its by-product. This type of fuel cells is used in transportations such as fleet vehicles and boats and space shuttles.

Table 7
Technical characteristics of different fuel cells.

Types of FC	Electrolyte	T (°C)	Fuel	Oxidant	Efficiency	Heat
Alkaline (AFC)	Potassium hydroxide (KOH)	50–100	Pure hydrogen or hydrazine	O_2/air	50–65%	Very low quality
Proton-exchange membrane (PEMFC)	Polymer, proton exchange membrane	50–80	Less pure hydrogen from hydrocarbons or methanol	O_2/air	40–50%	None
Phosphoric acid (PAFC)	Phosphoric acid	160–210	Hydrogen from hydrocarbons and alcohol	O_2/air	40–50%	Low quality
Sulphuric acid (SAFC)	Sulphuric acid	80–90	Alcohol or impure hydrogen	O_2/air	40–50%	None
Direct methanol (DMFC)	Polymer	60–200	Liquid methanol	O_2/air	40–55%	Very low quality
Molten carbonate (MCFC)	Molten salt such as nitrate, sulphate, carbonates...	630–650	Hydrogen, carbon monoxide, natural gas, propane, marine diesel	CO_2/O_2/air	50–60%	High quality
Solid oxide (SOFC)	Ceramic as stabilised zirconia and doped perovskite	800–1000	Natural gas or propane	O_2/air	50–60+%	High quality
Protonic ceramic (PCFC)	Thin membrane of barium cerium oxide	600–700	Hydrocarbons	O_2/air	45–60%	High quality

Parameters	AFC	PEMFC	PAFC	SAFC	DMFC	MCFC	SOFC	PCFC
Power density (W/cm^2)	0.2–0.35	0.35–0.36	0.2–0.25	0.2–0.3	0.04–0.23	0.1–0.2	0.24–0.3	0.2–0.3
Life time (10^3 h)	10–15	40–65	40–60	20–35	10–15	40–65	40–80	40–70
Cost/price* (US$/kW)	200	200	1000	800	200	100	1500	1500
Cell voltage (V)	1	1.1	1.1	1.1	0.2–0.4	0.7–1.0	0.8–1.0	0.8–1.0
Capacity	10 kW–100 kW	30 W, 1 kW, 2 kW, 5 kW, 7 kW, 250 kW	100 kW, 200 kW, 1.3 MW	100 kW, 200 kW, 1.3 MW	1 W to 1 kW, 100 kW to 1 MW (Research)	155 kW, 200 kW, 250 kW 1 MW, 2 MW	1 kW, 25 kW, 50 kW, 100 kW, 250 kW, 1.7 MW	1 kW, 5 kW, 25 kW, 100 kW, 150 kW, 1 MW
Reformer requirement	+	+	+	+	–	–	–	–

* Projected period 2010–2015 [29].

The PEMFC uses a solid polymer electrolyte (teflon-like membrane) to exchange the ions between two porous electrodes, which is an excellent conductor of protons and an insulator for electrons. They are well advanced type of fuel cell with higher power density; low operating temperature and quick start up suitable for cars and mass transportation.

The PAFC utilizes a liquid phosphoric acid as an electrode. The chemical reaction involved in this fuel cell is same as PEM fuel cell where pure hydrogen is used as its input fuel. The potential for hot water supply is also available as well as electricity depending on the heat and electricity load profile. More over PAFC have been installed at 70 sites in Europe, U.S.A. and Japan [30].

The SAFC utilizes a liquid sulphuric acid as an electrode. Its operating temperature is almost similar as compared to that of PEMFC. The chemical reaction involved in this fuel cell is same as PAFC where impure hydrogen is used as its input fuel.

The DMFC as a relatively new technology uses polymer electrolyte like PEMFC but uses liquid methanol or alcohol as fuel instead of reformed hydrogen fuel. During chemical reactions, the anode draws hydrogen by dissolving liquid methanol (CH_3OH) in water in order to eliminate the need of external reformer. At the cathode, the recombination of the positive and negative ions takes place, which are supplied from anode through external circuit and it is combined with oxidized air to produce water as a by-product.

The MCFC, operating at high temperature, has an internal reforming capability. It separates the hydrogen from carbon monoxide fuel and decomposition of hydrogen is taken through the water shift reaction to produce hydrogen, then the result of reaction is taken same as PEMFC to produce electricity. It also consists of two porous electrodes, in contact with a molten carbonate cell, and having a good conductivity.

The SOFC are basically high temperature fuel cells and a separate reformer is not required to extract hydrogen from the fuel due to its internal reforming capability. They use a solid ceramic material as its electrolyte, a dense yttria stabilized zirconia for example. The SOFC produce electricity at a high operating temperature and the combination of oxygen O^- with hydrogen H^+ generates water and heat. Much research is focussed on lowering the temperature to about 750 °C and even lower.

The PCFC, like SOFC, is developed basically with solid ceramic electrolyte material. It can electrochemically oxidize gaseous molecules of the hydrocarbon fuels directly supplied to the anode without the need of additional reformer since it can be operated at high temperatures of 700 °C. Additionally it has solid electrolyte, so the membrane cannot dry out as with PEMFCs or liquid cannot leak out as with PAFCs [31].

By far the greatest research interest throughout the world has focussed on Proton Exchange Membrane (PEM) Direct Methanol (DM) and Solid Oxide (SO) fuel cell stacks. PEMFC are well advanced type of fuel cell and very promising for mobile applications such as cars and mass transportation. DMFC are suitable for portable applications and should also be supported because of the simplification it brings to the overall system design and operability. SOFC is very promising for the very large market for medium power (kilowatts) devices. Its technology is the most demanding from a materials standpoint and is developed for its potential market competitiveness arising from:

- SOFCs are the most efficient (fuel input to electricity output) fuel cell electricity generator currently being developed world-wide.
- SOFCs are flexible in the choice of fuel such as carbon-based fuels and natural gas.
- SOFC technology is most suited to applications in the distributed generation (i.e., stationary power) market because its high conversion efficiency provides the greatest benefit when fuel costs are higher due to long fuel delivery systems to customer premises.
- SOFCs have a modular and solid state construction and do not present any moving parts, thereby are quiet enough to be installed indoors.
- The high operating temperature of SOFCs produces high quality heat byproduct which can be used for co-generation or for use in combined cycle applications.
- SOFCs do not contain noble metals that could be problematic in resource availability and price issue in high volume manufacture.
- SOFCs do not have problems with electrolyte management (liquid electrolytes, for example, which are corrosive and difficult to handle).
- SOFCs have extremely low emissions by eliminating the danger of carbon monoxide in exhaust gases, as any CO produced is converted to CO_2 at the high operating temperature.
- SOFCs have a potential long life expectancy of more than 40,000 to 80,000 h.

The efficiency of the SOFCs is currently the highest of all fuel cells and is around 80–90% along with a heat conversion possibility. With their very high efficiency, the useful high grade heat they produce plus the large market they could reach make them a very promising technology that will be a significant contributor within a portfolio of energy sources in the coming 10–20 years

Fig. 12 shows the efficiency potential of various power generation technologies. It is observed that the efficiency of FCs is always higher as compared with conventional distributed generation systems.

3.5. Fuel cells most needed uses

Combined with low noise and ability to utilise readily available fuel, FC generators are best suited for provision of power in utility applications due to the significant time required to reach operating temperatures and can have broad applications ranging from large-scale power plants, smaller home-scale power plants and portable/emergency power generators. FC could be used in many applications (Table 8); each proposed use raises its own issues and challenges. Their most needed uses are:

- Stationary applications and high power reliability: residential, UPS; emergency services such as hospitals and banking, industry, computer facilities, call centres, communication facilities, internet and telecommunications networks, telecommunication switching nodes, data processing centres and high technology manufacturing facilities, transmission towers, reception or other electronic devices that can benefit from the DC power supplied by a fuel cell.
- Emission minimisation or elimination: urban areas, industrial facilities, airports, zones with strict emissions standards.
- Limited access to utility grid: rural or remote areas, maximum grid capacity, the use of a FC for electrical power instead of a diesel generator, avoiding harmful emissions, help to preserve the environment and cause no problems noise to other people in the environment.
- Biological waste gases are available: waste treatment plants, fuel cells can convert waste gases to electricity and heat with minimal environment intrusion.
- Applications for transport: Most vehicle manufacturers are presently using fuel cell vehicles for research, development or testing. Regarding buses with fuel cells, in the last 4 years, a number of fuel cell buses have been in operation worldwide.

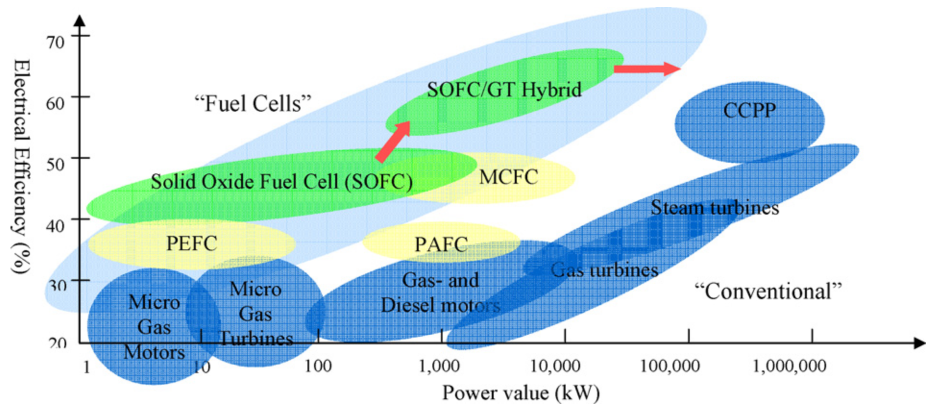

Fig. 12. Efficiency potential of various power generation technologies.

- Micro power: FCs are changing the world of telecommunications, since they can be used in mobile phones or laptops with a lot more battery life.
- Portable applications: FCs are used to replace batteries in mobiles; computers and other portable devices. FCs are also being used as supporting units when power shutdowns occur and in military applications. FCs are much lighter and more durable than batteries, which are particularly important for the soldiers during periods of military manoeuvres, and even more in case of war.
- CHP: FCs are suitable for CHP generation for buildings and industry, as well as for systems of district heating. With a growing tendency towards decentralised power generation, FCs will be attractive for small scale combined heat and power generation located at user sites.
- Space: Space applications, have sustained the interest in FCs which are becoming common in spaceflight (Space Shuttle, Skylab and Gemini spacecrafts).

In reality, the FCs differ in terms of characteristics, material used in construction and their suitability of applications.

It is noted that in addition to the civil applications set out in Table 8, there are many potential dual use application in the military sector.

4. Characteristics of fuel cells

A typical fuel cell polarization characteristic with electrical voltage against current density is shown in Fig. 13. The performance of the FC is improved by thermodynamics and electrical efficiency of the system [25]. The thermodynamic efficiency depends upon the fuel processing, water management and temperature control of the system. The electrical efficiency depends on the various losses over the fuel cells like ohmic loss, activation loss and concentration loss.

It can be seen that a linear region exists because as the current density increases the voltage drops due to its ohmic nature. This region is called ohmic polarization, it is mainly due to internal resistance offered by various components. At low current level, the ohmic loss becomes less significant; the increase in output voltage is mainly due to activity of the chemical reactions (time taken for warm up period). So this region is also called active polarization. At very high current density the voltage fall down significantly because of the reduction of gas exchange efficiency, it is mainly due to over flooding of waters in catalyst and this region is also called concentration polarization [32].

5. FCs and their environmental impact

Issues of efficiency and ecology converge at this time to renew interest in FCs as systems for electricity generation. In recent times, they attract serious attention in the utility industries, particularly in co-generation of heat and power. The environmental impact of SOFC use depends upon the source of hydrogen-rich fuel used. If pure hydrogen is used, fuel cells have virtually no emissions except water and heat. However, hydrogen is rarely used due to problems with storage and transportation, but in the future many people have predicted the growth of a solar hydrogen economy. In this scenario, photovoltaic cells would convert sunlight into electricity. This electricity would be used to split water (electrolysis) into hydrogen and oxygen, in order to store the sun's energy as hydrogen fuel [33]. In this scenario, FCs generating stations would have no real emissions of greenhouse or acid gases, or any other pollutants.

High efficiency of FC results in less fuel being consumed to produce a given amount of electricity, which corresponds to lower emission of carbon dioxide CO_2, the main "greenhouse gas" responsible for global warming. When hydrogen from natural gas is used as a fuel, FCs have no net emissions of CO_2 because any carbon released is taken from the atmosphere by photosynthetic plants. A reduction of carbon dioxide emissions by more than 2 million kg per year can be obtained [34]. Moreover, by skipping the combustion process that occurs in traditional power-generating methods, the

Table 8
Applications versus most suitable fuel cell technologies.

Size (kW rated)	Applications	User	Fuel cell technology
Micro (<1 kW)	Portable, personal	Commercial	PAFC/PEMFC
Small	Residential (high-value entry)	Utility/commercial	PAFC/PEMFC/SOFC
(1–5 kW)	Uninterruptible power (UPS)	Commercial	PAFC/PEMFC
	Remote applications	Utility	PAFC/PEMFC
Medium	Commercial/industrial	Utility	PAFC/MCFC/SOFC/PEMFC
(5–300 kW)	Automotive	Commercial/utility	PAFC/PEMFC
	Aircraft	Commercial	PAFC/PEMFC
	UPS	Commercial/utility	PAFC/MCFC/SOFC/PEMFC
Large (100 kW–50 MW)	Transportation (locomotives – buses)Aircraft/ships Energy industry	CommercialCommercial Commercial/utility	MCFC/SOFC, possibly in combination with a gas turbine

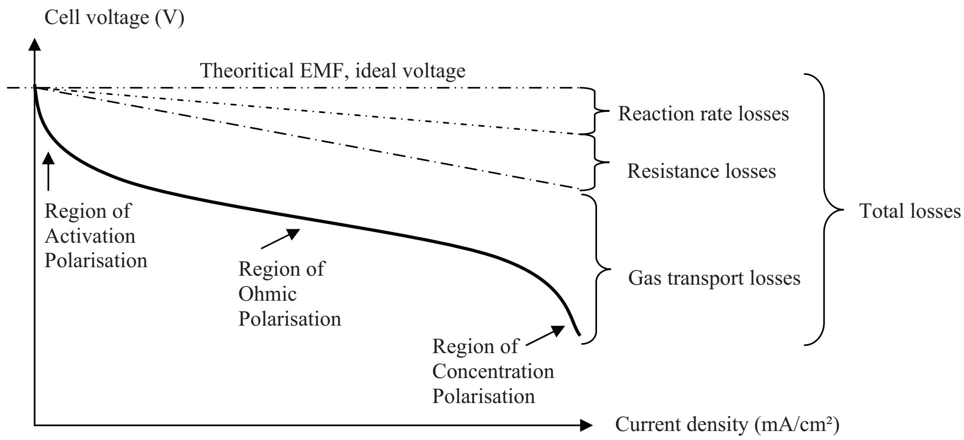

Fig. 13. Typical fuel cell polarization curve.

generation of pollutants during the combustion process is avoided. Emissions from FC systems will be very low with near-zero levels of NO_x, SO_x and particulates, therefore eliminates 20,000 kg of acid rain and smog-causing pollutants from the environment. In any case FCs generally provide the lowest emissions of any non-renewable power generation method such as traditional thermal power plants, as shown in Table 9 [35]. This is very important regarding energy related environment concerns.

When combined with a heat engine that uses any waste heat, FCs are the most clean and efficient devices available for this purpose. FC can also provide high-quality waste heat that can be used to warm the home or provide refrigeration and air conditioning without harming the environment. Armstrong says: “FCs only emissions are steam, trace amounts of nitrogen oxides and sulphur oxides, and a small amount of carbon dioxide”.

If CO_2 can be removed at the source for disposal elsewhere, the FC really would become the ultra-high efficiency, zero emissions power plant of the 21st century to open new research frontiers of environmental-friendly energy production system.

Hydrogen is rarely used due to problems with storage and transportation, but in the future many people have predicted the growth of a solar hydrogen economy.

6. Fuel sources

The fuels used in FCs just need to contain hydrogen but most contain carbon too, this fuel is reacted with oxygen from air, some fuel cells will need to reform the fuel if it is carbonaceous so that pure hydrogen is used but some will reform the fuel automatically. Some sources that spring to mind are:

- Methane – from drilling for natural gas, from decaying rubbish or sewage or gas hydrates
- Methanol/ethanol – from hydrolysing natural gas or biomass
- Hydrogen – from electrically dissociating water molecules or from using solar cells which dissociate water molecules.

6.1. Hydrogen sources and production methods

There is a growing consensus that hydrogen has the potential to supplement and possibly replace fossil fuels for the production of energy by 2010–2020. Hydrogen can be produced from a wide range of source materials, including fossil fuels, biomass, some industrial chemical by-products and water via electrolysis. The choice of source for a future hydrogen economy in worldwide, as elsewhere, would depend on various local factors including location of resources, available reserves, cost of extraction, cost of transportation and utilisation. The technique utilized to produce hydrogen from the source will depend on technology development, required infrastructure investment, efficiency, location and suitability of local supplies. Annual world production is currently around 5.4×10^{11} Nm^3 corresponding 2% of primary world energy demand [36]. Table 10 shows the principal production routes, indicating that 96% is produced from fossil fuels.

7. Benefits and applications of FC technologies

FCs have many advantages: they can be modular, they can be distributed to eliminate the need for transmission lines, and they operate quietly and are vibration free could provide higher system efficiency, higher power density, and simpler designs. At low enough costs, they could compete with combined cycle gas turbines for distributed applications. The benefits of FCs also include: energy security, reliability, low operating and maintenance cost and constant power production. FCs could be used in many applications. Fig. 14 illustrates the actual and estimated world demand on fuel cells [37,38,30,39].

7.1. FC system

The FC system which is depicted in Fig. 15 consists of four subsystems:

Table 9
Pollutant emission factors for the total portion of the fuel cycle.

Energy source	SO_x (gSO_x/kWh)	NO_x (gNO_x/kWh)	C in CO_2 (gC/kWh)	C in CO (gC/kWh)	Particles
Coal	3.400	1.8	322.8	40.0	0.00020
Oil	1.700	0.88	258.5	40.0	0.00015
Natural gas	0.001	0.9	178.0	20.0	0.00002
Nuclear	0.030	0.003	7.8	7.8	0.00005
Photovoltaics	0.020	0.007	5.3	1.3	0
Fuel cells	0	0	1.3	0.3	0

Table 10
Distribution of primary energy sources for world hydrogen production.

Primary source energy	SMR	OR	CG	E	Others
Distribution %	48.0	30.0	18	3.9	0.1

Primary source energy	SMR	OR	CG	E	N + SMR	NH + TC	SB	SP
H_2 production rate (tonnes/day)	150	–	150	–	7640	720	6	43

SMR, steam methane reforming; OR, oil reforming; CG, coal gasification; E, electrolysis; N + SMR, nuclear + steam methane reforming; NH + TC, nuclear heat + thermochemical cycle; SB, solar biomass; SP, solar photocatalysis.

Table 11
Desired performance targets and stretch goals for FC systems.

Parameter	Target	Stretch goal	Notes
Capital cost, installed ($/kW)	800	400	2010–2015 at 50,000 units/year
Power degradation	<1% per 1000 h	<0.5% per 1000 h	For year 2010–2015
Power density (mW/cm^2)	500	700	>4 cell stack and >25 cm^2 electrode

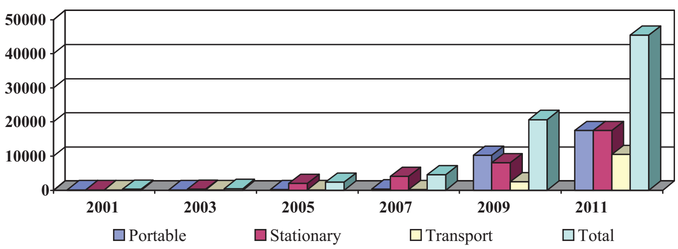

Fig. 14. Actual and estimated world wide fuel cells production (in million of $US).

- The gas handling system (or fuel processing) which provides the hydrogen and air (or oxygen) to the core being the FC proper.
- A heat management system.
- A power conversion unit.
- Regulation and control unit to supervise the operation of the plant.

This general layout can be substantially simplified by the use of Direct Current by the customer, which leaves the inverter out.

8. Recent development in FCs and their future

The optimal selection of size of the fuel cell is important to locate the fuel cell in distributed system to meet the peak load demands for different applications of utilities [40]. The various intermediate ranges of different FCs in markets from 0.5 kW to 2 MW are available [41].

Focusing their efforts on FCs, which have been on the verge of commercial viability for years, the researchers around the world are making a concerted effort for the development of suitable materials which are presently the key technical challenges facing FCs. For example, programs are underway in Japan and in U.S.A. that use a relatively simple ceramic process to develop a thin-film electrolyte that decreases the cell resistance and both doubles the power output and significantly reduces the cost of SOFCs. A nickel bisdiphosphine-based catalyst for fuel cells is demonstrated [42]. There is also current effort in integrating the FCs, developing a novel stacking geometry and increasing their life span more than 60,000 h. The demonstration of low-cost FC operation directly on methane signals an important new opportunity for making simple, cost-effective power plants [41]. Global FC making companies continues to realise very significant improvements in basic FC design. A measure of their success is the realisation of a 48.6% improvement in single cell power densities, since 2000, which represents the highest published power densities for commercial-sized FCs in the world [43]. Changes in cell composition and design have resulted in these improved power densities. Higher power densities contribute to lower weight, size and cost of FC systems.

FCs could someday be suitable for small-scale residential market applications if ultimate cost goals of $1000/kW are reached. Table 11 shows the California energy commission mid-term goals in the application of FCs, for the period 2010–2015 with a willing

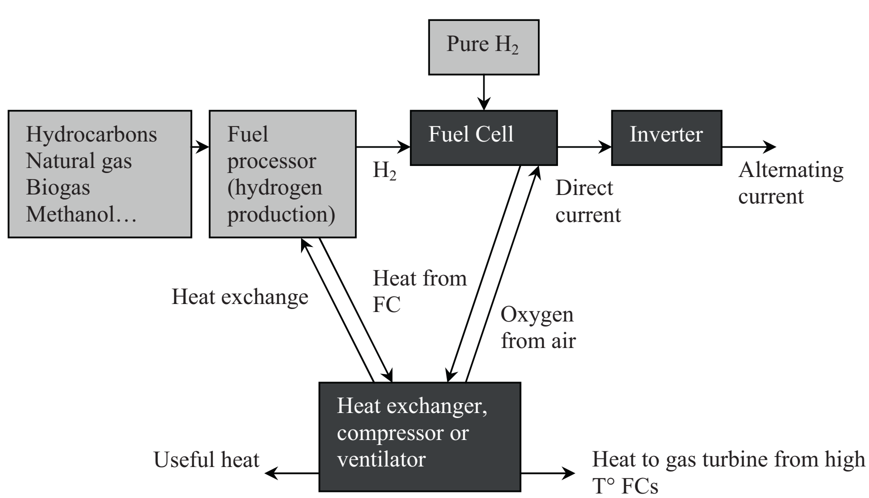

Fig. 15. General layout of a Fuel Cell system.

power density target of 300 mW/cm^2 and an installed capacity of 50,000 units/year [44].

The research is also focusing on development of 100 kW to 1 MW DMFC and other fuel cell types such as Direct Formic Acid FC (DFAFC), Direct Ethanol FC (DEFC) and Direct Borohydride FC (DBFC) for commercial applications [45].

9. Conclusion

Energy exploitation of fossil fuels is reaching its limits. Future alternatives must therefore be developed for long-term and environmental-friendly energy supply needed by a constantly growing world population. Clean power from FCs enables a clever global development strategy for solving the energy and climate problems with existing technologies and renewable energies availability for a 2050 world with 10 billion people in a sustainable way. Hydrogen FCs provide highly efficient, pollution free power generation. From the foregoing it is clear that new and improved materials have crucial role to play in FC development. Indeed materials scientist may well hold the key to the hydrogen economy. A new report unveiled recently by J. Barrett of the U.S. Economic Policy Institute (EPI) and J. A. Hoerner of the Centre for a Sustainable Economy (CSE), suggests that global warming can be reduced without harming the economy and that nobody needs to accept a choice between environmental degradation and economic calamity. A new global climate policy is needed and is possible. The Earth is subjected to severe environmental damage; therefore FCs are becoming a serious and credible option to substitute other technologies in electricity production.

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